

Scattering by slightly non-spherical particles on surfaces

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Abstract

We investigate the shape dependence of the scattering by dielectric and metallic particles on surfaces by considering particles whose free-space scattering properties are nearly identical. The scattering by metallic particles is found to be strongly dependent upon the shape of the particle in the region near where the particle and surface contact. These results have a significant impact on the use of light scattering to size and identify particles on surfaces.

1 Introduction

The inspection of surfaces for particles is an important step in the development of contamination-free manufacturing in the semiconductor, optics, and data storage industries. Tools based upon laser light scattering are often used to detect such contaminants. One of the challenges is to accurately identify the size and composition of contaminants, so that their source can be identified and the contamination problem solved. Multiple scattering channels, such as multiple detectors in a single-wavelength scanning system, are employed to provide information that can lead to particle identification and sizing. The development of these systems requires accurate scattering models for ideal and non-ideal particles, and appropriate interpretation of the results from those models.

In recent work, we presented results of calculations for scattering by some slightly nonspherical particles, which differed significantly from that by spherical particles of equal volume [1]. In particular, it was found that the scattering was strongly influenced by the shape of the particle in the region near where it contacted the surface. The calculations used an extension of a theory for scattering by spherical particles developed by Bobbert and Vlieger [2]. One criticism that can be placed on this work was that the extension of the theory is only valid when the particle is contained within a sphere above the substrate [3]. For some of the particles studied, this restriction was violated.

Here, we present new results which demonstrate the sensitivity, albeit within the constraints of the theory. The non-spherical particles are chosen so that they are entirely contained within a sphere which does not include the substrate. Furthermore, the particles are chosen such that their center of mass does not appreciably differ from that of a sphere of equal volume. The scattering is strongly dependent upon the shape of the particle near the point where it contacts the surface. The scattering is less sensitive to the shape variations when those variations are farther from the surface.

A number of studies have investigated the scattering by ellipsoids [4-7] and cylinders [7] on surfaces. However, since such particles scatter differently in free space than spheres of equal volume, the observations do not illustrate the effect the surface plays in the scattering. We choose instead to illustrate the effect of shape by considering particles whose free space scattering properties are very similar to spheres of equal volume. By choosing particles in this manner, we can effectively separate the effects that have to do with the global particle shape from those which result from the interaction with the surface.

2 Theory

An accurate theory for the scattering of light by spherical particles above a surface was developed by Bobbert and Vlieger [2] in 1986. Their method, which relies upon calculation of the reflection matrix

of the surface in terms of the vector spherical harmonics or spherical Debye potentials, can be straightforwardly extended to axisymmetric [4] and even arbitrary particles [5], by using the T-matrix approach of Barber and Hill [8], provided that the particle lies entirely within a sphere outside the substrate. For this study, we implemented the theory described in Ref. [4], and include the presence of a substrate coating by explicitly incorporating the appropriate reflection coefficients. We include the coating partly because such a layer normally exists on silicon and partly because its presence improves the rate of convergence of the solution. The T-matrix method used here was compared with the discrete-dipole method [9] using spherical and ellipsoidal (oblate and prolate) particles, yielding identical results within the accuracy of the discrete-dipole approximation.

3 Results

While the calculations were carried out for a variety of conditions, we will limit our presentation to some specific ones. The wavelength of 488 nm was chosen because the Ar⁺ laser line is commonly used in semiconductor wafer inspection tools. We use p-polarized (electric-field in the plane of incidence) light incident at an oblique angle $\theta_i = 60^\circ$, since an electric field perpendicular to the surface most strongly displays the effects that we show, and because oblique incidence and p-polarization yields larger scattering cross sections and are thus used in inspection applications. The particle materials will be limited to aluminum (index $n = 0.73 + 5.93i$), since it is a possible contaminant in wafer processing and has optical properties [$\text{Re}(n) < 1$] which enhance the effects which we show. We choose silicon with a 1.5 nm native oxide for the substrate, since it is a common material to inspect and, with its high index ($n = 4.37 + 0.08i$), yields a strong particle-substrate interaction. Scattering will be shown only in the plane of incidence, as a function of the scattering angle θ_r , measured from the surface normal; the results in out-of-plane directions are similar but are more difficult to visualize. The sign of θ_r is such that the specular condition occurs when $\theta_r = \theta_i$.

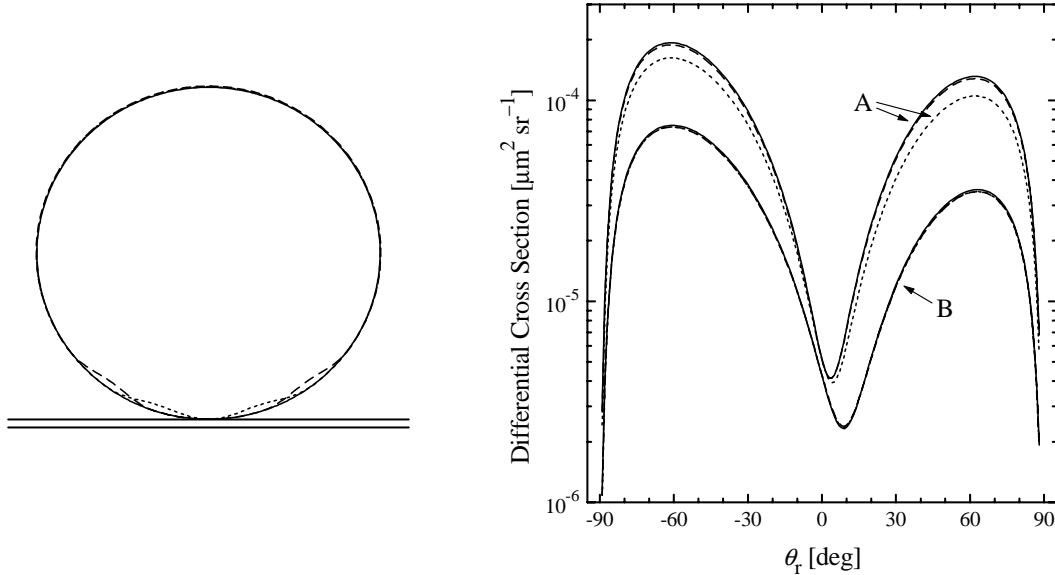


Fig. 1. The profiles of three particles are shown on the left. The calculated differential cross sections are shown on the right. The results of the full calculation, which includes the interaction of the particle with the substrate, are labeled A in the figure, while those which ignore the interaction are labeled B. The spherical particle is represented by solid curves.

Figure 1 shows the profiles of two axi-symmetric spherical particles which are spherical (with 30 nm radius) over most of their surfaces. One is non-spherical in a small region near the contact point, while the other is non-spherical in a region farther from the contact point. The shapes follow Chebyshev polynomials with maximum depth 1.2 nm in the non-spherical regions. Also shown in Fig. 1(a) is the

profile of a spherical particle having the same volume as the non-spherical particles. Figure 1(b) shows the calculated differential cross sections for the three particles, with and without including the interaction of the particle with the substrate. The three particles scatter nearly identically to each other if the interaction with the surface is ignored. That is, the particles behave the same in free space. However, when the interaction with the substrate is included, the scattering differs for the three particles. In particular, the particle having the perturbation nearest the contact point deviates significantly from the other two particles.

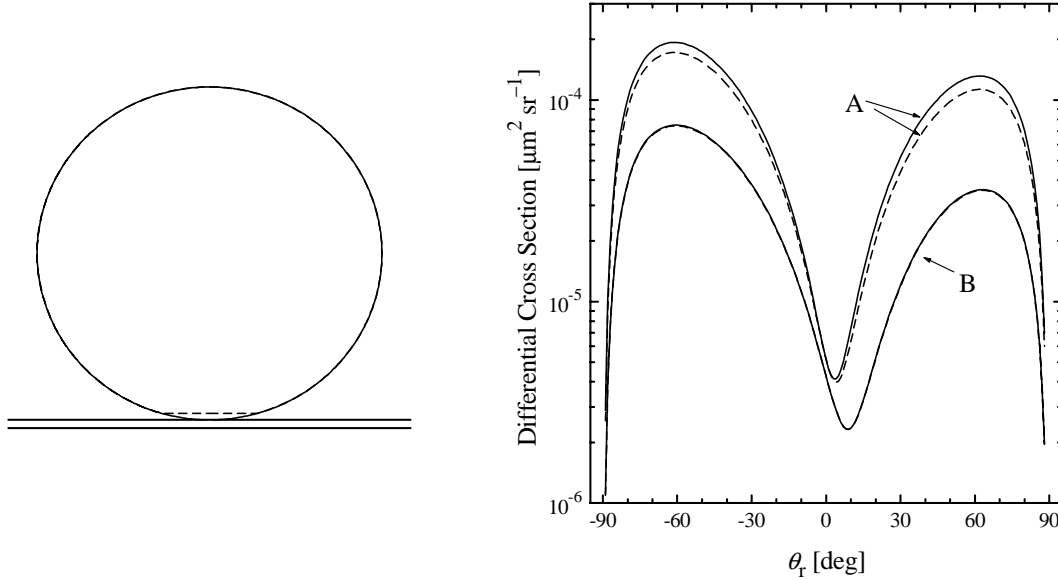


Fig. 2. Same as Fig. 1, but for different shapes.

Figure 2 shows results for a 60 nm spherical particle and one which is truncated by 1.2 nm and lying a distance 1.2 nm from the surface. Note that the truncated particle does not touch the surface and lies entirely within the other sphere. Like the particles shown in Fig. 1, the scattering by the isolated particles are nearly identical, yet the scattering by the particles near the substrate are significantly different.

Calculations performed using optical constants appropriate for polystyrene latex (PSL, index 1.605), show results whose differences are similar to those found when the near-field interaction is turned off. That is, the scattering by low index dielectric particles does not depend any more strongly on shape than that which is observed when the particles are isolated.

4 Discussion

Recent measurements have demonstrated that reference particles deposited on substrates may be sized by optical scattering measurements. Determination of the size and assessment of the uncertainty requires accurate models for the scattering of particles, not only in their ideal condition (say, as spheres), but also in their non-ideal conditions (as rough or deformed particles). An elastic sphere bound to a surface is expected to deform to yield a nonzero contact area. This contact area can be estimated using the theory of Johnson, Kendall, and Roberts (JKR) [10], and depends upon the work of adhesion, the radius of the sphere, and the Young's moduli and Poisson ratios of the materials. For a polystyrene sphere adsorbed on an oxidized silicon substrate, the radius of the contact area can be estimated to be about a ~ 6 nm, corresponding to an indentation of about 0.6 nm, for a 30 nm radius sphere. The shape of the particle will not exactly match that of the particles described above [10], but the dented-sphere model provides an estimate of the magnitude of the effects that are expected to occur. The uncertainties in the diameters of polystyrene calibration particles approach 1 % of their

diameters [11]. The finite contact area can have a small but significant impact on the scattering by standard polystyrene spheres, when they are placed on a wafer surface.

The primary concern to those inspecting surfaces for particulate contaminants is the ability for the instruments to correctly size and identify the material. While the scattering from dielectric particles shows much less sensitivity on shape, as they deviate from spherical, the scattering from aluminum particles shows a strong dependence on shape. The particles described here are all chosen to be only slightly different from spherical, and they qualitatively lie well within the range of what most any inspector would want to consider as identical particles. However, the scattering by the three aluminum particles shown in Fig. 1 differ by as much as 20 % to 30 % at angles where the scattering is strongest. Such a change in scattering cross section may be incorrectly interpreted by assigning an incorrect size (as much as 5 % error in diameter) or an incorrect material to the detected particle. In conclusion, analysis of light scattering to characterize particle size and material must take into account the possibility that real particles will have non-ideal shapes, which differ only slightly from ideal ones.

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